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Influence of ballast conditions on flexural responses of railway concrete sleepers

Sakdirat Kaewunruen[*,1, 2], Alex M Remennikov[2]

[1]*Austrak Pty Ltd, Head Office, Brisbane, Queensland, 4105 Australia*

[2]*School of Civil, Mining, and Environmental Engineering, Faculty of Engineering,*
University of Wollongong, Wollongong, NSW 2522 Australia

Summary:

Railway sleepers in track systems are usually modeled using the beam on elastic foundation theory. In reality, the sleeper-supported ballast is of highly frictional granular media but does not provide any tensile resistance. This paper presents a finite element model of a railway sleeper in a track system, taking into account the tensionless nature of the elastic support. The highlight of this paper is the effect of ballast distributions on the flexural responses of railway sleepers in track systems. Using a finite element package STRAND7, the finite element model updating of the concrete sleeper was earlier developed and validated against experimental dynamic characteristics by the authors. The numerical model is capable of simulating the tensionless ballast support whereas the supporting boundary condition provides resistance to only compression. The numerical simulations are demonstrated as to investigate the quasi-static bending moment resultants of the railway concrete sleeper against the current design methodology. This study explores the effectiveness of the provision in the current design code for bending moment calculations under various support conditions.

Keywords: railway concrete sleeper, sleeper/ballast interaction, nonlinear static analysis, flexure, tensionless support.

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[*] Corresponding author. Tel.: +61 2 4221 4588; fax: +61 2 4221 3238.
E-mail addresses: skaewunruen@austrak.com (S. Kaewunruen), alexrem@uow.edu.au (AM. Remennikov)

1. Technical Backgound

The railway sleepers (also called 'railroad tie') are a main part of railway track structures. Its major role is to distribute loads from the rail foot to the underlying ballast bed. Based on the current design approach, the design life span of the concrete sleepers is targeted at around 50 years [1]. Fig. 1 shows the typical ballasted railway tracks and their components. There are a number of investigations on the railway sleeper models [2-5]. Most of the models employed the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. It is found that only vertical stiffness is sufficient to simulate the ballast support condition because the lateral stiffness seems to play an insignificant role in sleeper's bending responses [6].

Australian Standard for railway prestressed concrete sleepers [1] prescribes the method for evaluating the bending moments for the design of railway concrete sleepers. Although the most critical loading conditions on the track systems are related to wheel impacts, the current design procedure takes the dynamic effects into account by using a dynamic load factor and treats the wheel burden as the quasi-static loading [7]. In practice, the wheel load generally imparts the positive bending moment at the railseat whilst provides the negative bending moment at mid span of the railway sleepers. For a standard or broad gauge sleeper, the design maximum positive bending moment at the rail seat, M_{R+}, can be evaluated by

$$M_{R+} = \frac{R(L-g)}{8} \qquad (1)$$

where R is the rail seat load, L is the total length of sleeper, and g is the gauge length of the track. It should be noted that the length of ballast support beneath each railseat (a) can be calculated by $a = L - g$ [1].

Analogously, the centre negative design bending moment M_{C-} for track gauge of 1,600mm and greater reads [1]:

$$M_{C-} = \frac{1}{2}\left[Rg - Wg(L-g) - \frac{1}{8}W(2g-L)^2 \right] \tag{2}$$

where

$$W = \frac{4R}{3L-2g} \tag{3}$$

Noteworthy, the design cross sections and reinforcements deemed to comply with the Australian Standard shall provide adequate shear resistance [1]. Even though the sleeper cross-section plays a vital role on its flexural strength, the responses of the railway sleepers are insignificantly dependent to either the bending rigidity or the modulus of elasticity of sleepers [8]. This paper presents the effect of ballast conditions on the flexural responses of railway sleepers. It focuses on the nonlinear flexural response of railway concrete sleepers subjected to a spectrum of ballast stiffnesses including the asymmetrical ballast condition due to the improper ballast tamping/packing [9], in comparison with the current design method in accordance with the Australian Standard AS1085.14 [1]. The dynamic bending of railway sleepers under transient loadings has been carried out and can be found in the companion paper [10].

2. Finite element analysis

It has been established that the two-dimensional Timoshenko beam model is the most suitable option for modeling concrete sleepers [2-5]. In this investigation, the finite element model of a concrete sleeper has been previously developed and calibrated against the numerical and experimental modal parameters [5, 9]. Fig. 2 shows the two-dimensional finite element model for an in-situ railway concrete sleeper. Using a general-purpose finite element package STRAND7 [11], the numerical model included the beam elements, which take into account shear and flexural deformations, for modeling the concrete sleeper. The trapezoidal cross-section was assigned to the sleeper elements. The rails and rail pads at railseats were simulated using a series of spring. In this study, the sleeper behaviour is stressed so that very small stiffness values were assigned to these springs. In reality, the ballast support is made of loose, coarse, granular materials with high internal friction. It is often a mix of crushed stone, gravel, and crushed gravel through a specific particle size distribution. It should be noted that the ballast provides resistance to compression only. As a result, the use of elastic foundation in the current standard [1] does not well represent the real uplift behaviour of sleepers in hogging moment region. In this study, the support condition was simulated using the tensionless beam support feature in Strand7 [11]. This attribute allows the beam to lift over the support while the tensile supporting stiffness is omitted. The tensionless support option can correctly represent the ballast characteristics in real tracks [11]. Table 1 shows the geometrical and material properties of the finite element model. It is important to note that the parameters in Table 1 give a representation of a specific rail track. These data have been validated and the verification results have been presented elsewhere [5, 9].

To our knowledge, the nonlinear response analysis of railway concrete sleepers in a track system due to the variation of ballast support conditions has not yet addressed by the research workers. Especially when the uplift behaviour due to ballast tensionless support in hogging region of sleepers is considered, a finite element analysis is required to supersede the simple manual calculation. The numerical simulations are conducted using the nonlinear solver in STRAND7 [11], in order to study the effect of ballast stiffness and asymmetrical support conditions on the flexural response of the railway concrete sleeper in a track system.

3. Flexural moment responses

Using the design data in Table 1, Fig. 3 shows the bending moment diagram along the sleeper when subjected to the equal wheel loads of 100kN at both railseats, in comparison with the standard design moments. Based on Equations (1) and (2) in accordance with AS1085.14 [1], the design maximum positive bending moment at the rail seat M_{R+} = 12.50 kNm, while the centre negative design bending moment M_{C-} = 6.95 kNm. It is typical that the positive and negative moments are associated with the railseat and mid-span sections, respectively. It shows that the standard design moments provide the conservative results. The standard design moment at mid span is about half between the other two cases (see Fig. 3). The effect of ballast stiffness on the moment resultant is presented in Fig. 4. The nominal bending moments M^* at both rail seat and mid span are normalized by the standard design moments at rail seat (M_{R+}) and mid span (M_{C-}), respectively. Also, the ballast stiffness increment is presented in terms of the variation of percent changes from the initial ballast data in Table 1. It is found that the static bending moments of the railway sleeper are conservatively estimated by the design standard. For the bending moment at rail seats, the small discrepancies between the standard design moments and the nominal moments varying from four to ten percent can be noticed. At mid span, the negative design moments seem to be significantly overestimated by roughly seventy to eighty percent. It appears that the bending moments have low sensitivity to the spectrum of ballast stiffnesses in general.

To evaluate the effect of asymmetrical support conditions on the flexural response of the concrete sleeper, the ballast support at the right hand side (see Fig. 5) is scaled at factors varied from 0.0 to 2.0 (or 0 to 200 percent of w_R/w_L), while the support at the left hand side is kept at constant [9]. Fig. 6 illustrates the bending moment of the railway sleeper due to the uneven ballast stiffness distribution. It should be noted that the normalization is based on the standard design moments in accordance with the Australian Standard [1]. Fig. 6 exhibits that the asymmetrical ballast support tends to have little effect on the rail seat moment resultant, except for the unsupported condition. It is found that the ballast support conditions play a significant role in the nominal bending moment at mid span of the railway sleeper. Especially during the lacking period of ballast support, the nominal bending moment at mid span rises up to eight times of the standard design moment. The effect of asymmetrical ballast support tends to decrease nonlinearly as the ballast support stiffness increases to the balanced condition. However, the unbalanced support distribution has little influence on the bending moment resultants when the other rail seat is sufficiently supported. The implication of this study to railway construction practice is that the sleeper will perform well as designed when the tamping of ballast has been made properly. Although the over-tamping of ballast could have been conducted, the sleeper responses would experience less loading effect in service. In general practice, railmen are to install the rails at both rail seats of sleepers considering the accurate width of rail gauge (wheel axle length). To achieve the accurate rail gauge, this study shows that those railmen should also carry out the proper tamping of fresh ballast or re-tamping of the broken or fouled one.

4. Conclusion

This paper numerically investigates the critical static effect of a variety of ballast conditions on the flexural responses of the railway concrete sleepers in a track system. The finite element model of concrete sleepers, which was established and calibrated earlier, is utilized in this study. The effects of the variation of ballast stiffness together with the asymmetrical ballast distribution on the bending of the railway sleeper were highlighted in comparison with the standard design. The nonlinear solver in STRAND7 was employed to handle sleeper/ballast contact mechanics. Under static and quasi-static conditions for equally supported sleepers, the numerical results exhibit that the bending moment resultants are affected slightly by the ballast stiffness variation. The standard design bending moments tend to be overestimated by averagely ten percent for the positive bending moment at both rail seats and by about seventy percent for the negative bending moment at mid span. On the other hand, the bending moment resultants are affected significantly by the uneven ballast stiffness distribution, in particular for the situation of lacking support. In such case, the nominal bending moment at mid span could be larger than the standard design moment up to eight times. The insight in bending moment distribution has raised the awareness of track engineers for the proper maintenance of the ballast condition.

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Table 1 Engineering properties of the standard sleeper used in the modeling

Parameter lists		
Flexural rigidity	$EI_c = 4.60$, $EI_r = 6.41$	$\mathrm{MN/m^2}$
Shear rigidity	$\kappa GA_c = 502$, $\kappa GA_r = 628$	MN
Ballast stiffness	$k_b = 13$	$\mathrm{MN/m^2}$
Rail pad stiffness	$k_p = 17$	MN/m
Sleeper density	$\rho_s = 2{,}750$	$\mathrm{kg/m^3}$
Sleeper length	$L = 2.5$	m
Rail gauge	$g = 1.5$	m

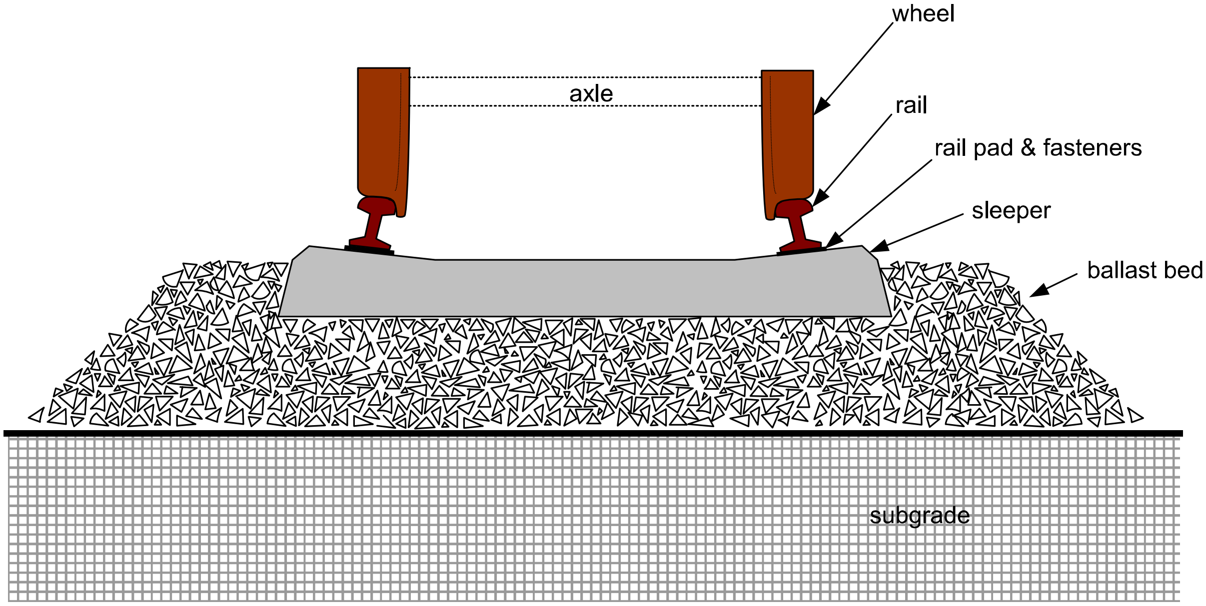


Fig. 1. Typical railway track system

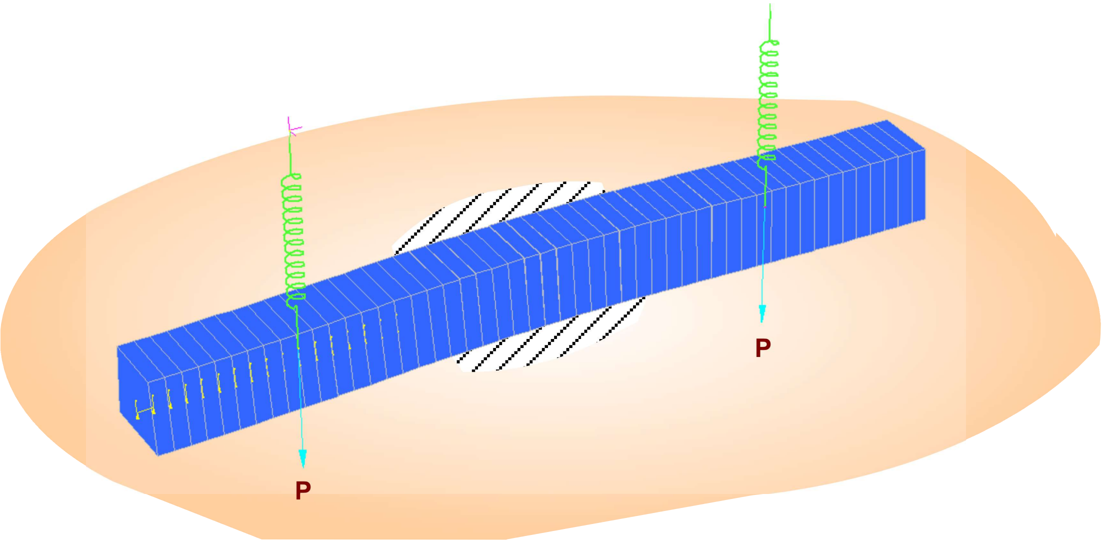
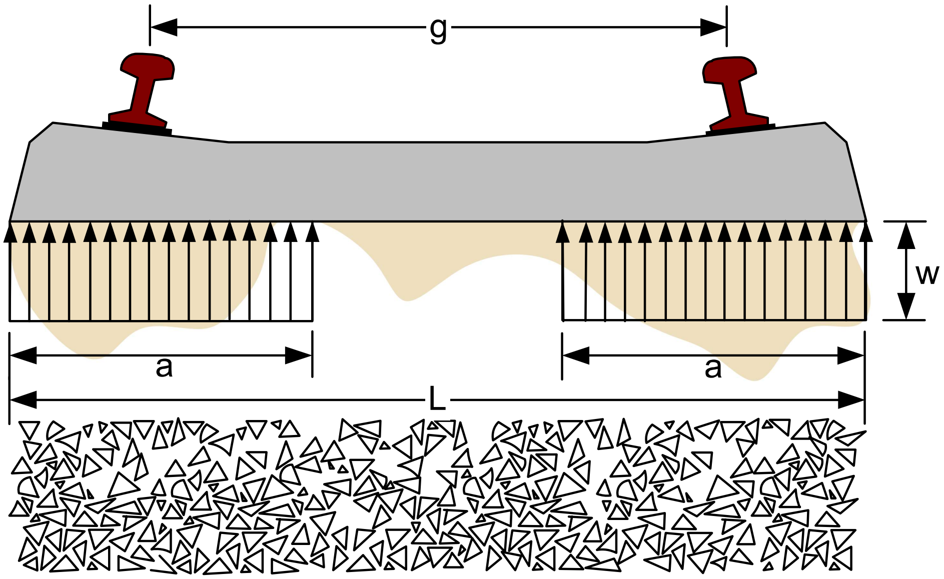
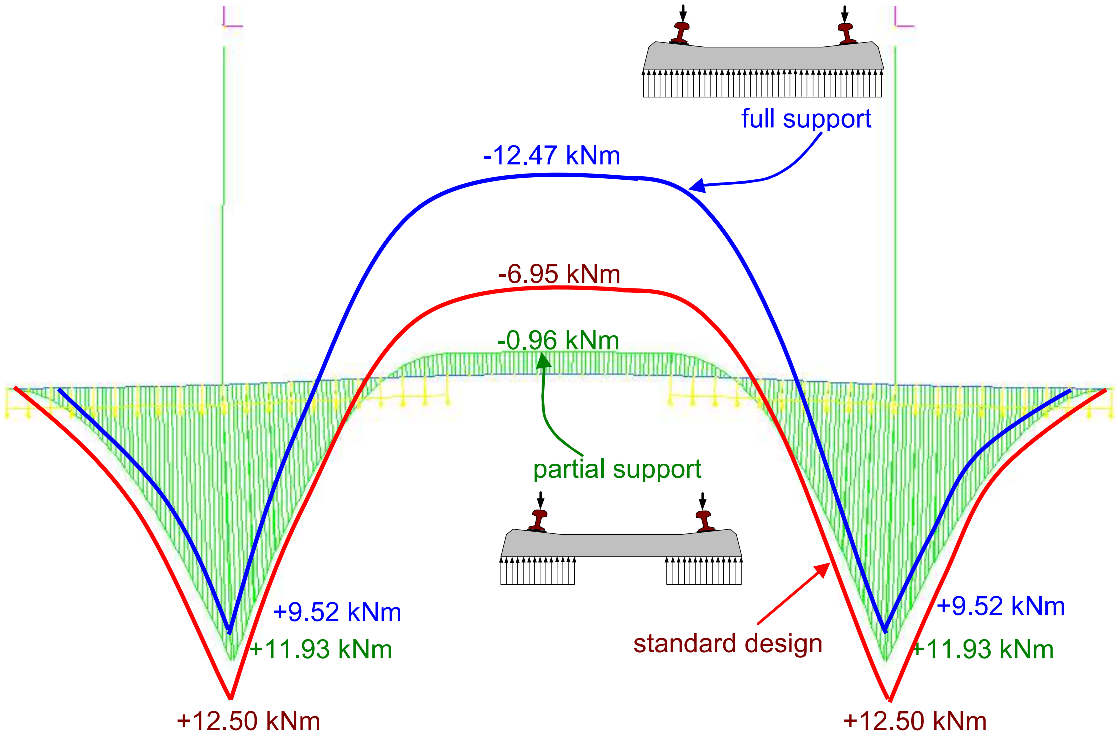


Fig. 2. STRAND7 finite element model of a concrete sleeper



a) symmetrical ballast support condition [1]



b) bending moments of railway sleeper

Fig. 3. Flexural response of a railway sleeper in track system

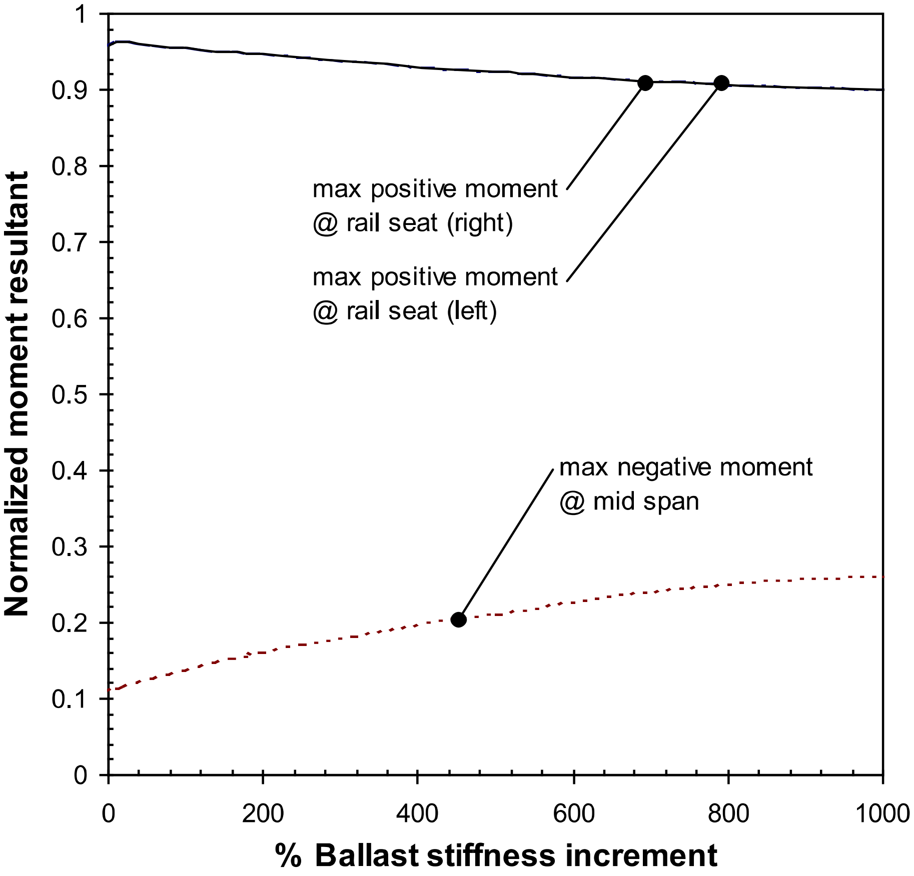


Fig. 4. Effect of the variation of ballast stiffness

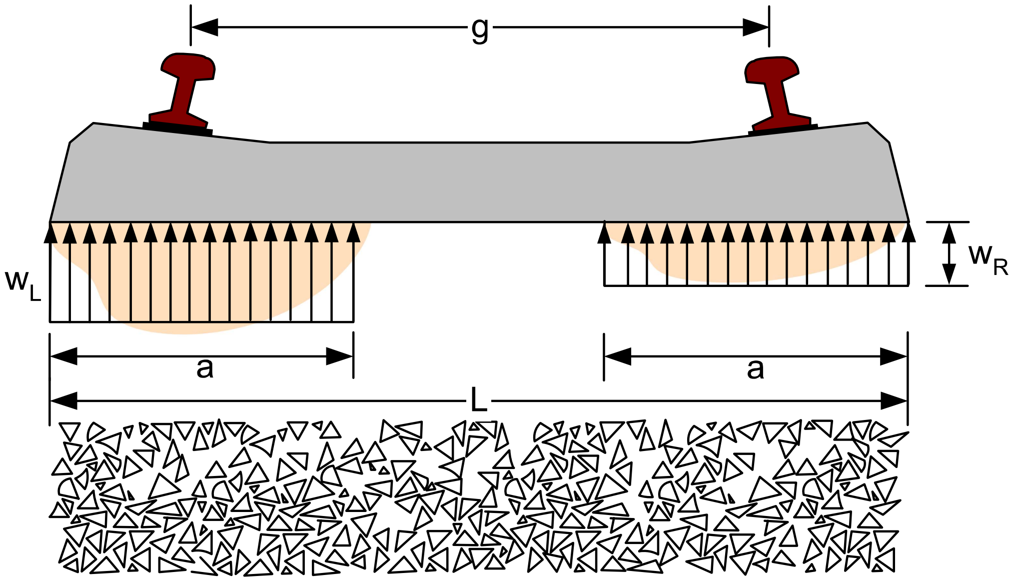


Fig. 5. Asymmetrical ballast stiffness distribution

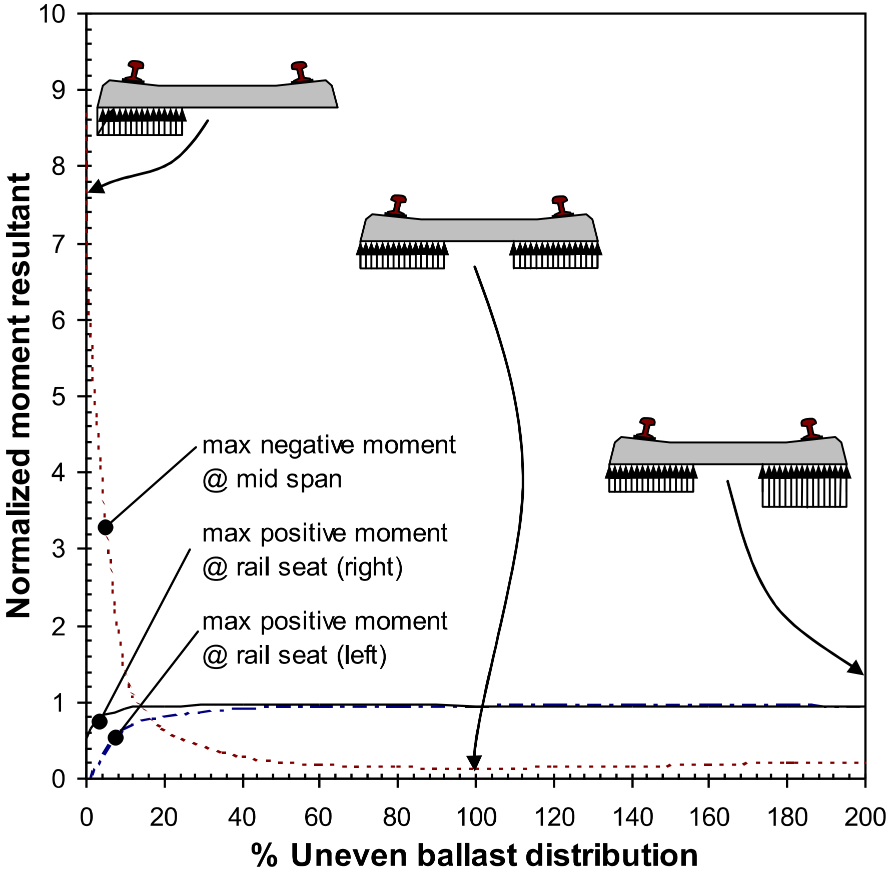


Fig. 6. Effect of asymmetrical ballast support